SLR 2000: AN AUTONOMOUS AND EYESAFE SATELLITE LASER RANGING STATION

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ABSTRACT

SLR 2000 is a system concept for an autonomous, unmanned satellite laser ranging station with a single shot range precision of one centimeter or better. The goal of the program is to provide 24 hour tracking coverage and to reduce both capitalization and operating and maintenance costs by an order of magnitude relative to current outlays. The dominant cost driver in present systems is the onsite manpower required to operate the system, to service and maintain the complex subsystems (most notably the laser), and to ensure that the transmitted laser beam is not a hazard to onsite personnel or overflying aircraft. In performing initial tradeoff studies of the SLR 2000 system, preference was given to simple hardware over complex and to passive techniques over active resulting in the concept described here. The SLR 2000 system consists of an optical head mounted to a concrete pier which in turn contains a single rack of electronic equipment. Temperature inside the pier and instrument is controlled by a small heat pump. The system communicates via Internet with a central scheduler/data processor for the purposes of obtaining updated satellite schedules and orbits and transmitting range and ancillary data and general housekeeping information.

To keep the cost of the tracking telescope and mount subsystems within reasonable bounds, the SLR 2000 telescope aperture is being constrained to diameters between 30 and 50 cm, which is comparable in size to present transportable systems. Single pulse energy is maximized, within eye hazard constraints, by filling the available aperture with the transmit beam and by using passive aperture sharing or polarization techniques, rather than active transmit/receive switches, to separate the transmitted and received beams. Taking into account cumulative multiple pulse effects on the human retina, the maximum allowable transmitted energy per pulse is only 350 microjoules and 90 microjoules for the fundamental (1064 nm) and frequency-doubled (532 nm) wavelengths of Nd:YAG respectively. Our baseline design assumes use of the green wavelength with APD or MCP/PMT detection, but final selection will depend on the success of external NASA programs in developing a high speed, high quantum efficiency infrared detector.

To counteract the negative effect of a roughly three order of magnitude reduction in laser energy relative to present systems, SLR 2000 must operate at roughly Khz pulse repetition rates with a narrower beam divergence on the order of 10 arcseconds (between $1/e^2$ intensity points) in order to achieve a minimum 100 range measurements within a two minute LAGEOS normal point bin. Such rates and energies can be achieved by relatively simple diode pumped and Q-switched microlasers and passive multipass amplifiers, thereby eliminating the need for unreliable flashlamps and associated high voltage power supplies, complex switching and modulation electronics, and long., thermally stable resonators. Furthermore, microlaser packages are sufficiently lightweight and compact that they can be mounted to the same structure as the telescope, eliminating the need for multimirror Coude systems and vastly improving alignment stability. Beam divergence can be adapted to the satellite being tracked.

To handle the higher repetition rates, event timers similar to those used in lunar laser ranging (LLR) will most likely displace single stop time interval counters in present systems. Station epoch time will be maintained to better than 50 nsec by a GPS-steered quartz or rubidium oscillator. More effective spectral, spatial, and temporal filtering will be required to maintain desirable signal to noise ratios during daylight ranging to LAGEOS. Real time data processing techniques, such as Poisson filtering (adapted from LLR), are being used in combination with frequently updated orbits from the central processor to isolate data from noise and to narrow the range gate.

1. INTRODUCTION

SLR 2000 is a system concept for an autonomous, unmanned satellite laser ranging station with a single shot range precision of one centimeter or better. The motivation for developing SLR 2000 stems from the realization that:

SLR provides unique and important science
SLR is more expensive than competing radio techniques
SLR costs can be reduced through increased reliability, standardization, and automation
New technologies are available which can greatly reduce system complexity and cost

The goal of the SLR 2000 program is to provide full 24 hour tracking coverage and to reduce both capitalization and operating and maintenance costs by an order of magnitude relative to current outlays. The dominant cost driver in present systems is the onsite manpower required to operate the system, to service and maintain the complex subsystems (most notably the laser), and to ensure that the transmitted laser beam is not a hazard to onsite personnel or overflying aircraft. Thus, the primary technical goals of the SLR 2000 system are:

Unmanned, eyesafe operation
24 hour tracking of LAGEOS and lower satellites
One centimeter (RMS) single shot precision or better
Minimum 100 ranges per normal point
Mean time between failures: > 4 months
Automated two-way communications with a central data processor via Internet
System free of optical, electrical, and chemical hazards

Secondary goals for the system, presently viewed as highly desirable but perhaps difficult to achieve, include a capability to range to high altitude satellites such as GPS, GLONASS, and ETALON and the ability to retrofit two color technology at some later date.

In performing initial tradeoff studies of the SLR 2000 system, preference was given to simple hardware over complex and to passive techniques over active resulting in the concept to be described here. In our current technical approach, the SLR 2000 system consists of an optical head mounted to a concrete pier which in turn serves simultaneously as the basic geodetic monument and as an environmental shelter housing a single rack of electronic equipment as in Figure 1. The temperature inside the pier and instrument is controlled by a small heat pump. The system communicates via Internet with a central scheduler/data processor for the purposes of obtaining updated satellite schedules and orbits and transmitting range and ancillary data and general housekeeping information.

In this paper, we perform some fundamental system level analyses which have guided the preliminary design of SLR 2000 and provide an overview of the system. Greater engineering detail is given in companion papers located elsewhere in these proceedings.

2. EYE SAFETY CONSIDERATIONS

To keep the cost of the tracking telescope and mount subsystems within reasonable bounds, the SLR 2000 telescope aperture is presently constrained, at least initially, to about 30 cm, which is comparable in size to present NASA transportable systems. Furthermore, it was decided early in our deliberations that eyesafe beams are to be preferred over active aircraft radars in ensuring eye safety. Taking this passive approach has several important advantages. From an engineering and economic standpoint, the passive eyesafe approach is absolutely failsafe and eliminates the need for an additional large and expensive aircraft radar subsystem. Furthermore, from a political and legal standpoint, it should be easier to obtain approval from local regulatory agencies, such as the Federal Aviation Administration (FAA) in the United States for such a system to operate in an unattended mode. The principal disadvantage is that combining the eyesafe requirement with the small aperture results in a maximum single pulse energy which is significantly less than a millijoule at the visible and near infrared wavelengths commonly used in SLR. As we shall see shortly when we discuss probability of detection, SLR 2000 must operate at roughly Khz pulse repetition rates with a narrower beam divergence on the order of 10 arcseconds (between $1/e^2$ intensity points) in order to counteract the negative effect of a roughly three order of magnitude reduction in laser energy relative to present systems and to achieve a minimum 100 range measurements within a two minute LAGEOS normal point bin. However, such rates and energies can be easily achieved by a relatively simple Q-switched microlaser followed by a single multipass amplifier. It is demonstrated elsewhere that a Nd:YAG microlaser operates most efficiently at roughly a 2 Khz rate when pumped by a CW diode [Degnan and Dallas, 1994].

Microlasers can be efficiently pumped by low voltage CW laser diodes, thereby eliminating the need for unreliable flashlamps and their associated high voltage triggering circuits and power supplies, water-to-air heat exchangers and their associated plumbing, complex switching and modulation electronics, and long., thermally stable resonators. Microlasers can passively generate single picosecond pulses due to their extremely small lengths on the order of a mm and hence do not require fast, high voltage electro-optic switches or modulators or carcinogenic dyes as do conventional modelocked systems. Furthermore, these microlaser packages are sufficiently lightweight and compact that they can be mounted to the same structure as the telescope, eliminating the need for multimirror Coude systems and vastly improving long term alignment stability.

Clearly, single pulse energy is maximized, within the eye hazard constraints, by filling the available aperture with the transmit beam. In calculating the eyesafe energy at a particular wavelength according to U.S. ANSI standards , one must take into account cumulative multiple pulse effects on the human retina. For visible wavelengths, readily seen by the observer, a reaction or integration time of 0.25 seconds must be assumed. For infrared wavelengths, invisible to the observer, the ANSI standards require longer integration times on the order of ten seconds.

Assuming a repetition rate of 2 Khz and a 30 cm telescope aperture and taking into account cumulative multiple pulse effects on the human retina as required by current U.S. ANSI eye safety standards, one obtains a curve for the maximum allowable energy as a function of laser wavelength given in Figure 2. The maximum allowable transmitted energy per pulse is only 350 microjoules for the fundamental (1064 nm) and about 90 microjoules for the frequency-doubled (532 nm) wavelengths of Nd:YAG respectively. Our baseline design assumes use of the green wavelength with SPAD or MCP/PMT detection, but final selection will depend on the success of external NASA programs directed at developing a longlived, high speed, high quantum efficiency detector for use at infrared wavelengths beyond 1 micron.

In the author's opinion, the use of so-called "eyesafe" wavelengths longer than about 1.06 microns does not, at least at the present time, offer any real advantages to SLR 2000. These wavelength regions suffer from relatively inefficient, low gain, and technologically immature laser materials and exotic detector materials typically characterized by relatively low quantum efficiency and high internal noise. Furthermore, going to longer wavelengths to take advantage of the higher eyesafe pulse energies reintroduces many of the undesirable features of high energy laser systems which are largely eliminated by the use of the low energy, diode-pumped microlaser. For example, high energy lasers must be pumped either by flashlamps (with their accompanying large high voltage power supplies and cooling systems) or by rather expensive high power laser diode arrays. Furthermore, these larger lasers are more likely to damage optics and cannot be directly mounted to a small telescope which then requires the use of a more complex Coude or similar multimirror system, further increasing cost and endangering the long term reliability and alignment stability in an unattended mode.

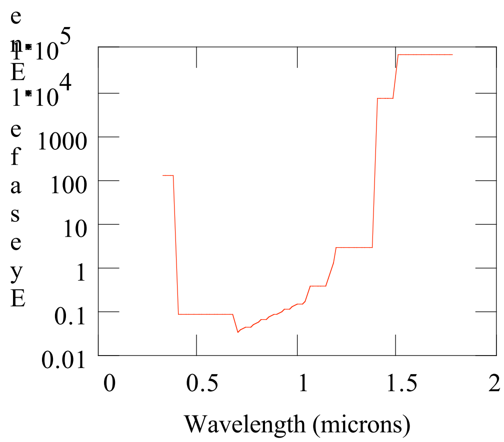

Figure 2: The eyesafe energy as a function of wavelength for a system operating at a repetition rate of 2 Khz with a transmitting aperture of 30 cm.

3. PROBABILITY OF DETECTION

The probability of detection is governed by Poisson statistics according to the equation

$$P_D = 1 - e^{-n_s} \sum_{m=0}^{m=n_t-1} \frac{n_s^{\ m}}{m!} \tag{1}$$

where n_s is the mean number of received signal photoelectrons and n_t is the detection threshold in photoelectrons [Degnan, 1993]. In designing the SLR 2000 system, we have imposed the requirement that at least 100 single range measurements are obtained in constructing a normal point. Thus, if we have a single shot range with a random uncertainty of $\pm$ 1 cm, the resulting normal point will have a random uncertainty of $\pm$ 1 mm. An SLR 2000 system operating at a repetition rate of 2 Khz sends out a total of 240,000 ranging pulses over the two minute normal point bin for LAGEOS. Hence, only a very small fraction of these (0.042%) must be detected to satisfy the 100 minimum ranges per normal point criteria. Figure 3 is a plot of the number of range returns per normal point as a function of the mean number of received photoelectrons, n_s, and the detection threshold (n_t = 1, 2 and 3 pe) for a LAGEOS normal point time bin of two minutes and a system repetition rate of 2 Khz. Under our criteria of a minimum hundred ranges per normal point, a threshold of 1 pe can accomodate mean signal strengths below 0.001 pe, a 2 pe threshold requires a mean signal strength of about 0.03 pe, and a 3 pe threshold requires a mean signal strength of about 0.15 pe.

4. FALSE ALARM RATE

It is clear from Figure 3 that a lower detection threshold implies a greater number of range returns in the normal point bin, but it also increases the number of false alarms generated by the background and detector noise rates. Noise in a laser ranging system can generally be reduced through four types of predetection filtering - spectral , spatial, temporal, or amplitude filtering [Degnan, 1985]. However, powerful post-detection discrimination can also be provided by Poisson filtering techniques which have long been used by the lunar ranging community [Abbott et al,1973], and these algorithms are currently being adapted for SLR 2000 [McGarry et al, 1994].

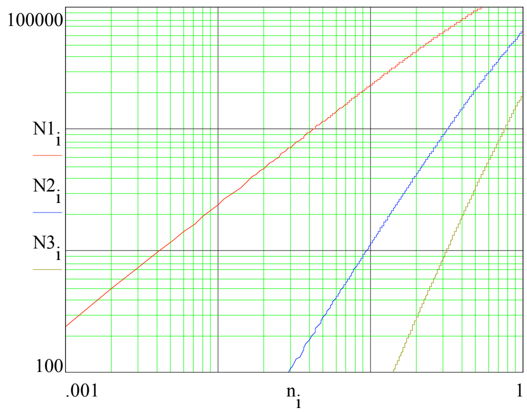

Figure 3: The number of range returns per normal point is plotted as a function of the mean number of received photoelectrons, n_s, and the detection threshold (n_t = 1, 2 and 3 pe) for a LAGEOS normal point time bin of two minutes and a system repetition rate of 2 Khz. Under our criteria of a minimum hundred ranges per normal point, a threshold of 1 pe can accomodate mean signal strengths below 0.001 pe, a 2 pe threshold requires a mean signal strength of about 0.03 pe, and a 3 pe threshold requires a mean signal strength of about 0.15 pe.

The following table lists some spectral filters produced by various manufacturers along their minimum bandpasses, typical throughputs, and field-of-view (FOV) or acceptance angle.

TABLE 1: Some spectral filters and their characteristics.

DEVICE	SOURCE	TRANSMISSION (%)	BANDWIDTH (nm)	FOV (Deg)
Bandpass	Omega	70	1.0 nm	
Bandpass	Omega	53%	0.3 nm	
Photo-refractive	Accuwave	15%	0.0125 nm	1.6
SADOF*	Shay,NMSU	60%?	0.002 nm	2-5?

*SADOF = Stark Anomalous Dispersion Optical Filter

The bandpass of a static spectral filter must be wide enough to accomodate the laser pulsewidth and any Doppler effects created by the moving satellite. Figure 4a shows the laser pulse bandwidth as a function of pulsewidth while Figure 4b describes the maximum Doppler shift induced by the satellite motion as a function of altitude. Both curves are bounded in the vertical by the relatively inexpensive and polarization-insensitive 0.3 nm Omega bandpass filter and by the significantly more expensive and polarization-sensitive Accuwave photorefractive filter. It is clear from Figure 4 that the photorefractive filter begins to reduce signal throughput for laser pulsewidths less than about 80 picoseconds and for satellite altitudes less than about 4000 Km. An “ideal” static filter, with a bandpass on the order of a few hundredths of a nanometer, would accomodate both effects for the current range of satellite altitudes between 400 and 20,000 Km. Active tunable filters, which can track out the Doppler shift based on a priori knowledge of the satellite motion, were also briefly considered for SLR 2000. However, computer simulations [McGarry et al, 1996] have demonstrated the ability of postdetection Poisson filtering techniques to easily cope with SNR ratios smaller than 0.05. Thus, in keeping with our preference for passive over active techniques and commercially available components over R&D components, our baseline design assumes a simple static filter with a readily attainable bandpass on the order of 0.12 nm.

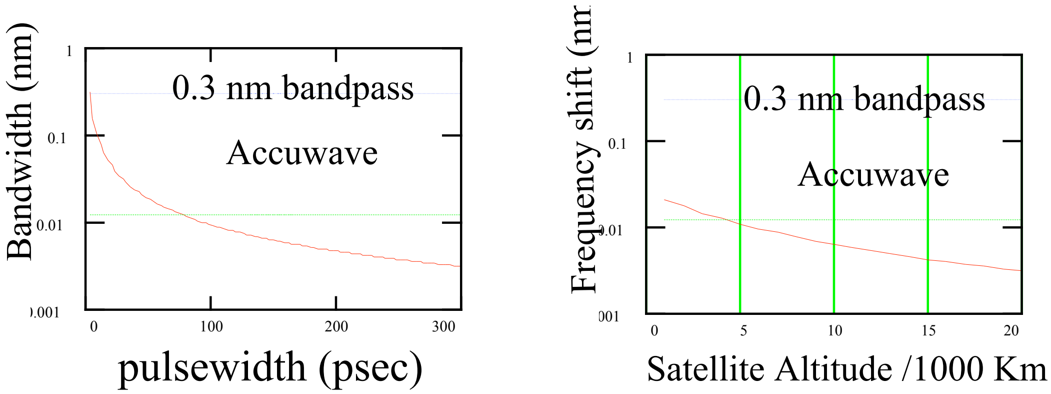

Figure 4: The effect of laser pulsewidth (a) and satellite Doppler (b) on the spectral filter specifications. The Doppler shift produced by low satellites places a lower bound of a few hundredths of a nanometer on the bandpass of a static spectral filter. The same filter could accomodate microlaser pulsewidths greater than 50 psec.

Link calculations suggest that a beam divergence of about 40 microradians (full angle between Gaussian $1/e^2$ intensity points) is appropriate for reliable and robust tracking of LAGEOS. If we design the receiver spatial filter to approximately match this transmitter field of view, we obtain the false alarm rates due to typical daylight background noise shown in Figure 5. We have assumed a detection threshold of one photoelectron and have allowed the range gate to vary between 10 and 1000 nsec. The upper and lower curves represent the number of false alarms generated within one two minute LAGEOS normal point using the Omega 0.3 nm and Accuwave 0.0125 nm spectral filters respectively.

The curves in Figure 5 include background noise effects but do not include false alarms generated by internal detector noise. While this is a negligible effect for microchannel plate photomultiplier (MCP/PMT) detection, it can be a significant factor for Single Photoelectron Avalanche Photodiode (SPAD) detection. On the other hand, SPADs are compact, offer improved sensitivity and quantum efficiency, and are easily adapted to the Khz repetition rates needed by SLR 2000. Furthermore, signal related biases, often observed in larger more energetic systems which currently use SPAD's, are not an issue for SLR 2000 because of its low mean signal strengths which typically fall well below 1 pe for most satellites.

5. SYSTEM OVERVIEW

Figure 6 provides a block diagram of the overall SLR 2000 system. Orbital predicts are generated by a central processor using the latest available data from the global network and provided to the onsite Data Processing/Scheduling computer via the Internet. The latter computer sends back laser range data and other system information over the Internet link to the Central Processor. The InterRange Vectors (IRV's) are passed to the onsite Control Computer which generates realtime pointing commands to the telescope via the dual axis servo drivers as well as range gates to the receiver subsystem. Incremental inductasyn encoders and resolvers on the mount axes pass the absolute pointing information back to the Control Computer. As an illustration of a commercial product which meets the functional requirements of SLR 2000, the Aerotech's Model 360-D series of tracking mounts and their Unidex 500 series of driver/controllers is designed for a PC-bus interface, has subarcsecond resolution, few arcsecond absolute accuracy, and can handle telescope apertures up to 50 cm.

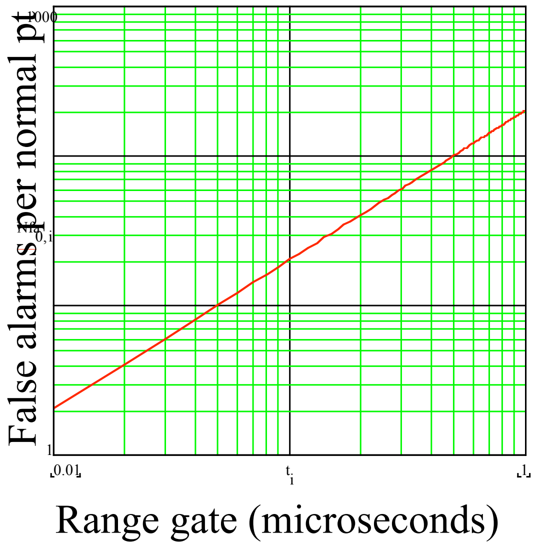

Figure 5: The number of false alarms produced in a sincle LAGEOS normal point frame (2 minutes) by solar scattering in the atmosphere during daylight tracking on a clear day. The curves assume matching transmitter and receiver FOV's (40 microradians), a 1 pe detection threshold, a range gate operating at 2 Khz with a variable window between 10 and 1000 nsec. The curve assumes the Accuwave 0.0125 nm spectral filter and scales linearly with spectral bandpass.

Absolute pointing accuracy is maintained over long intervals through periodic automated star calibrations using a CCD array within the optical pointing assembly. Epoch time is passed to the control computer by a GPS-disciplined oscillator. The best commercial device at present is the Hewlett-Packard Model 58503A GPS Time and Frequency Reference Receiver which combines the excellent short term stability of the internal quartz oscillator with the long term stability provided by GPS time intercomparison and frequency updating. With a GPS satellite in view, the unit provides a 1 pps output synchronized to better than 100 nsec relative to USNO. Jitter is less than 50 nsec. It also provides a 10 Mhz signal with a frequency accuracy better than 1 part in 10^{12} (one day average) when locked. We are also investigating the possible use of a GPS-disciplined rubidium oscillator which would have improved stability characteristics [Ingold et al, 1994].

The PC-based Control Computer enables the microlaser/amplifier by switching on a programmable DC power supply. The repetition rate of the passively Q-switched microlaser can be controlled by adjusting the power of the diode laser that pumps the oscillator. This feature can be used, if necessary, to ensure that returning pulses from the satellite do not arrive coincidentally with the blanking of the receiver during pulse transmission by varying the PRF over a narrow range. The passively Q-switched microlaser is discussed elsewhere in these proceedings [Degnan and Dallas, 1994].

In some instances, it may be beneficial to increase the beam divergence to acquire and track the lower satellites for which orbit predictions are generally poorer but signal strengths are higher. A simple, low-risk approach to accomplishing this is to adjust the spacing in the transmitter magnifying optics by inserting AR coated etalons with different thicknesses via a rotating wheel assembly activated by the Control Computer. Alternatively, an electronically controlled zoom lens assembly can be used to decollimate the beam prior to entering the fixed telescope.

Mechanical Transmit/Receive (T/R) switches, such as rotating mirrors or coated disks, are commonly used in the laser network where typical laser fire rates are between 5 and 10 Hz. However, mechanical techniques are not readily adapted to the Khz pulse rates required by SLR 2000. Furthermore, mechanical devices often lose synchronization and require field maintenance. However, other non-mechanical active T/R switch approaches exist which do have the requisite switching speed and include electro-optic, acousto-optic, and frustrated internal reflection. However, our design philosophy of simplicity and reliability drives us to examine totally passive options first.

Two totally passive approaches to the T/R switch are aperture sharing and polarization rotation. Aperture sharing, in which different regions of the primary are used by the transmitter and receiver respectively, has been used successfully on NASA's TLRS-2 system for 10 years . While feasible, aperture sharing may not be the most efficient option for the eyesafe SLR 2000 system since the received signal is maximized by having both the transmit and receive beams use the full aperture of the primary and increases as D^4 where D is the diameter of the telescope primary.

The principal disadvantage of the polarization rotation approach, shown in Figure 7, is that the receiver is polarization-sensitive, i.e. it will only see the linear component of polarization transmitted to the detector. This is not an issue if the circular polarization of the laser beam is faithfully maintained during its flight to and from the satellite, but recent theoretical calculations [Arnold, 1994] suggest that satellites with uncoated retroreflectors (at this time, just LAGEOS 1 and 2), which rely on total internal reflection, can severely depolarize the incoming laser light resulting in a substantial loss of throughput to the detector at some satellite orientations. The majority of satellites have retroreflectors with metallized back surfaces and apparently do not exhibit this effect. Care must also be exercised in designing the transmit/receive optics since the reflection of beams with arbitrary polarization properties off dielectric interfaces at nonzero incidence angles can also lead to polarization changes. The final T/R switch approach will be decided on following further experimental investigations at GSFC of the magnitude of the depolarization effect using our 1.2 meter telescope ranging off LAGEOS.

Figure 7: A polarization rotation T/R switch. The p-polarized laser radiation is transmitted through a polarizer and a quarter-wave plate converts it to circularly polarized light. Upon returning from the satellite, a second passage through the quarter wave plate converts the photons to s-polarization which are then reflected by the polarizer into the detector.

In our baseline concept, the received beam at 532 nm will pass through a conventional 0.3 nm Omega narrowband spectral filter (or possibly a 10 nm filter augmented by a Sigma Corporation 0.12 nm etalon filter), a focusing lens, variable spatial filter, and a gated SPAD detector with a quantum efficiency between 20 and 40%, as presently used by the Wettzell and Helwan SLR stations. An epoch timer and programmable range gate generator, currently being developed by AlliedSignal Technical Services Corporation (ATSC) for the Italian Matera Laser Ranging Observatory (MLRO), can be adapted to operate at 2Khz rates for SLR 2000 [Varghese et al, 1994]. Our baseline approach to range calibration is the use of external targets although internal calibration schemes will also be considered.

The system will also incorporate external meteorological sensors (see Figure 1) for the accurate measurement of pressure, temperature, and humidity and return these data over the Internet along with the range data. The tracking mount and optical head will be equipped with military-style connectors and seals to protect the system bearings and electrical connections from the environment. Temperature within the system shelter will be controlled by a small heat pump serviced and maintained through a local service contract. The site host or a local cleaning service will be enlisted to periodically inspect and clean the optics, and a skilled technician will visit the system every four to six months to perform higher level maintenance tasks. Internal sensors and diagnostic subroutines will continuously monitor the health of the various subsystems and report anomalies over the Internet link so that repairs can be initiated either remotely or through an onsite visit by a field technician. Although SLR 2000 will typically be housed at protected military, government, or university sites, additional automated sensors will monitor motion, wind speed, visibility, and rain to provide additional system security.

Using the latest data available, the central data processor will update the orbit parameters and time biases for the various satellites, and the updated data will be accessed via the Internet by the onsite Data Processing/Scheduling computer. This, combined with periodic automated star calibrations, will greatly reduce the initial angular uncertainty in pointing and speed acquisition. Poisson filtering techniques will be used in both the initial acquisition and autotracking of the satellite. The autotracking algorithms will distinguish the satellite data from the background and detector noise and then center and narrow the range gates to further enhance the SNR. System simulations have demonstrated the ability to lock onto the satellite within seconds [McGarry et al, 1996]. We are also investigating whether or not detection of the unused radiation at 1064 nm by a small infrared array might aid in the acquisition and autotracking process without robbing too much energy from the green ranging beam [Titterton et al, 1995].

6. SUMMARY

We have described some preliminary concepts for a fully automated, eyesafe satellite laser ranging system Most of the subsystems can presently be acquired commercially at a relatively low cost, and we believe that, following the initial development of some specialized components and the system software, the total system can be replicated in kit form for under $250,000 USD. Approximately 40% of the total cost is associated with the high resolution, high accuracy tracking mount. Unique subsystems, for which we have not yet identified a commercial source, include the microlaser transmitter, high repetition rate epoch timer and range gating circuitry, and the gated array used in acquisition and pointing. These will be developed inhouse or on contract as extrapolations of existing commercial devices which nearly meet our requirements.

ACKNOWLEDGEMENTS: The author wishes to acknowledge several people who have contributed to the SLR 2000 concept: Jan McGarry and Joseph Dallas of the NASA Goddard Space Flight Center; Paul Titterton and Harold Sweeney of EOO, Inc.; Brion Conklin, Tom Oldham, Howard Donovan, Tom Varghese, and Bill Bane of AlliedSignal Technical Services Corporation; and Peter Dunn of Hughes STX.

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